U.S. DEPARTMENT OF ENERGY | Nuclear Energy

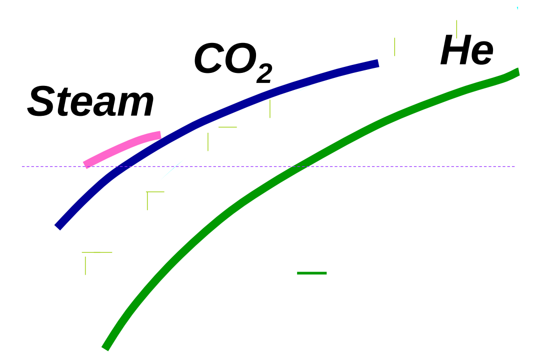
Advanced Reactor Technology- Supercritical Carbon Dioxide Brayton Cycle R&D

Gary E. Rochau
Manager, Advanced Nuclear Concepts
Sandia National Laboratories

NRT Summit
March 22, 2012

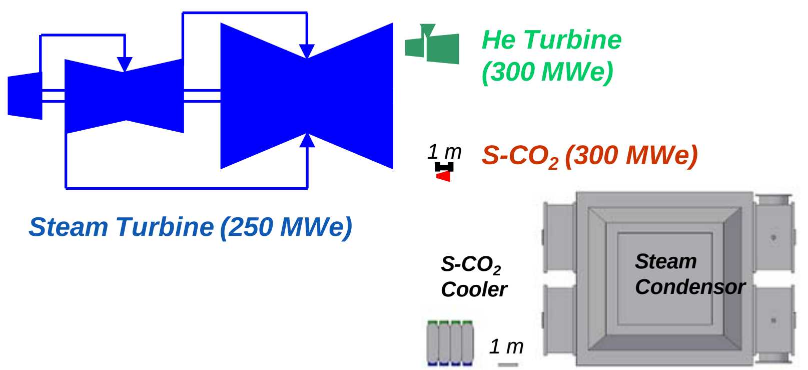
S-CO2 Turbomachinery Demonstration Program Objectives

- **Highest thermal/electrical conversion efficiency**
- **Demonstrate Super-Critical Carbon Dioxide (S-CO2) Brayton cycle capability**
- **Demonstrate up to 50% conversion efficiency**
- **1/10 of the System volume**
- **1/100th of the cost**



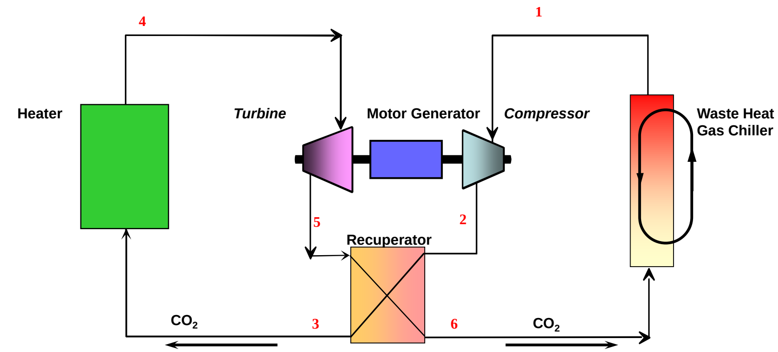
Rejects Heat
Above Critical Point
High Efficiency *Non-Ideal Gas*
Sufficiently High for Dry Cooling

Critical Point
88 F / 31 C
1070 psia / 7.3 MPa

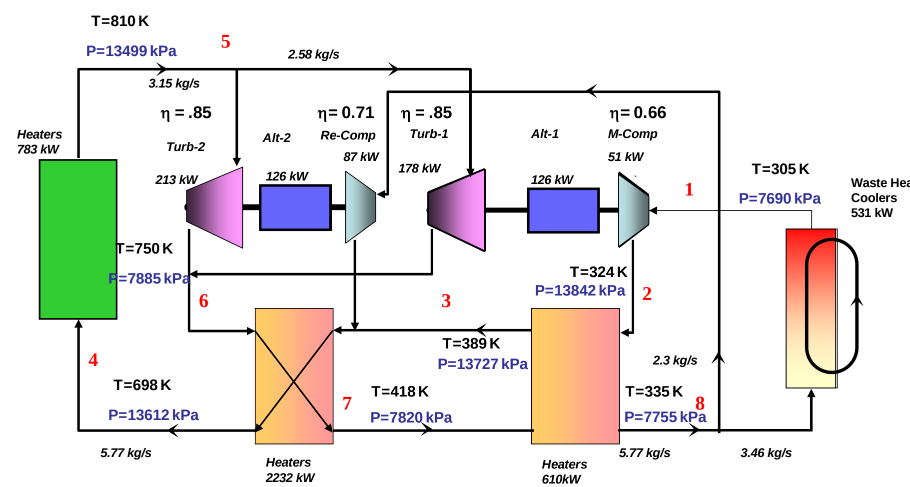


Brayton Cycle History

- **2005 Sandia demonstrated a closed Brayton cycle using gases for space propulsion,**
- **2007 initial investigation into the stability of S-CO_2 as a working fluid very near the fluid's critical point – a thermodynamic state in which fluid properties vary dramatically.**
- **2009 DOE funded development of a series of more extensive test article**
  - S-CO2 Compressor Loop
  - S-CO2 Simple Brayton Loop
  - S-CO2 Split-Flow, Fully recuperated, Recompression Brayton Loop
- **2009 Developed Compressor Maps for various gases and mixtures**
- **2010 Demonstrated operation of the Simple Brayton Cycle**
- **2011 Demonstrated operation of the Split-Flow Brayton Cycle.**
- **March 2012 – Shipment of Split Flow Loop to Sandia**



Simple Brayton Loop



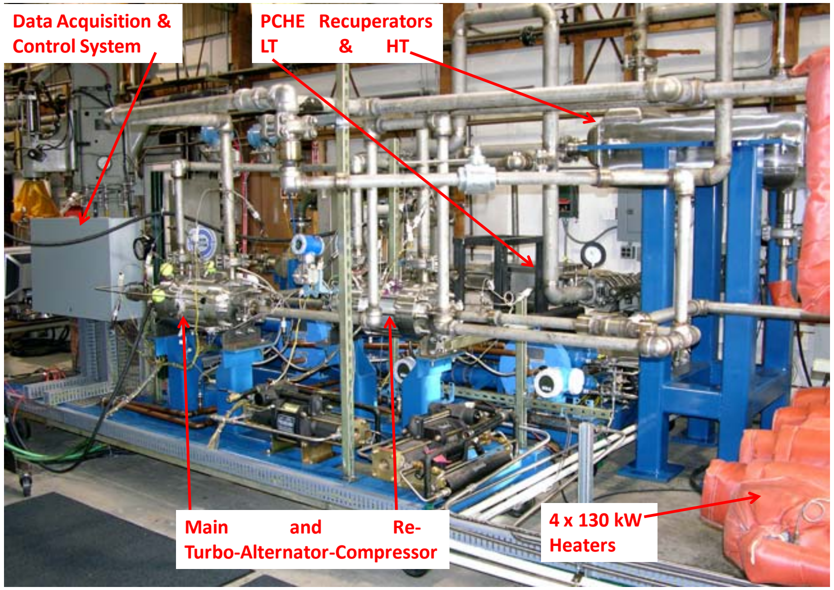
Split-flow, Fully Recuperated, Recompression Brayton Loop

Sandia S-CO2 Brayton Loops

Nuclear Energy

- Two Turbine-Alternator-Compressors (TAC's) designed to produce 125 kW of electricity each,
- A bank of heaters with 780 kW capacity,
- Two recuperators to transfer heat from the high temperature flow exiting the turbine to the low temperature flow exiting the compressors, and
- A heat rejection heat exchanger.

Low Pressure Simple Brayton Loop

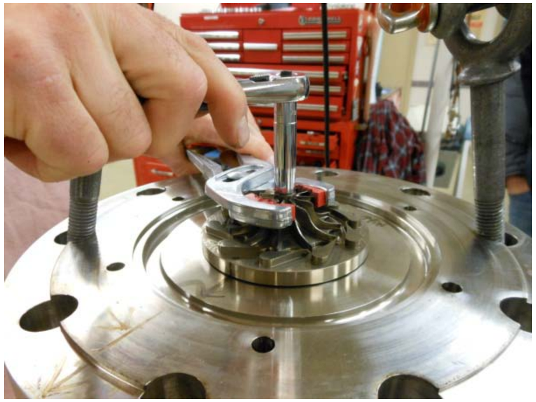


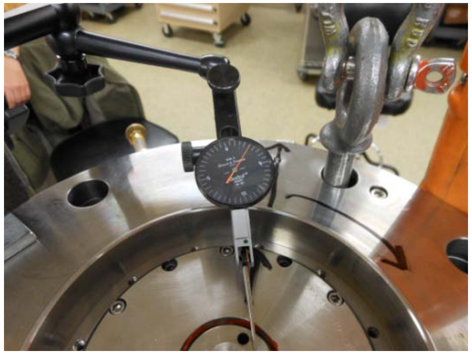
S-CO2 Split Flow Brayton Loop

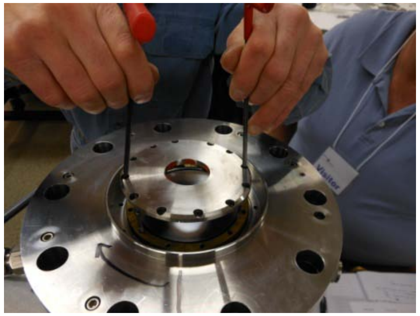
S-CO2 Brayton Compressor Loop

Specialty training at Barber Nichols before loop delivery

- **TAC teardown**
  - Complete disassembly of TAC A and B
  - Used for trouble shooting various turbo machinery problems
    - *i.e. failed bearings, break away torque out of spec., rubbed turbo machinery...*
  - Developed SNL-OP-TT001 which is a procedure to disassemble the TAC unit
- **TAC clearance adjustment**
  - Several crucial adjustments are present in each TAC unit
    - *i.e. turbine, compressor, and recompressor clearance from respective shrouds.*
  - Developed SNL-OP-CT001 which is a procedure to verify the clearances in both TAC units
- **TAC assembly**
  - Complete assembly of TAC A and B
  - Used for replacing various turbo machinery components
    - *i.e. failed bearings, rubbed turbo machinery, shrouds, and sensors...*
  - Developed SNL-OP-AT001 which is a procedure to assemble the TAC unit







Expedited Schedule

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

February 20th – 24th
TAC disassembly and reconfiguration

March 12th – 16th
Final loop upgrades completed

March 19th –23st
Acceptance testing of completed test article at BNI

March 22nd– 30th
Complete disassembly, packaged for shipment and shipment

April 2nd– June 29th
Assembly and commissioning of newly installed SCO2 Brayton loop

Delivery and Construction

Unloading zone for multiple semi trucks

Staging area for off loaded equipment

S-CO2 Brayton Cycle

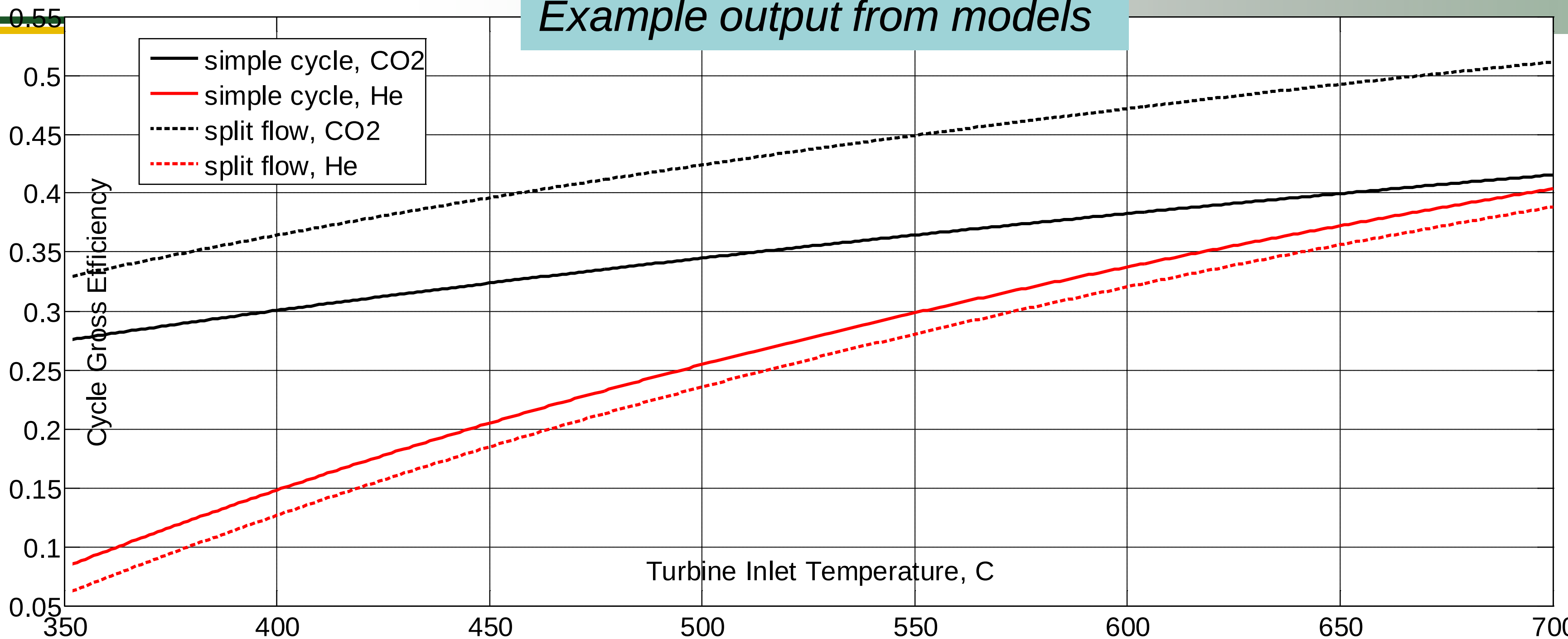
- *Major system upgrades are nearly completed to attain the original testing capabilities of:*
  - *75,000 RPM on both Turbo-Alternator-Compressor (TAC) units.*
  - *780 kWth input power.*
  - *Peak operating temperature of 1000°F.*
  - *Peak operating pressure of 18.7 MPa.*
  - *5.7 kg/sec mass flow rate.*
  - *Net power generation on the order of 250 kWe.*
- *Recent focus has been to:*
  - *Complete upgrades.*
  - *Perform acceptance testing of the upgraded test article (TA) at the contractor facility.*
  - *Prepare test facility site at Sandia, Albuquerque (see photos at right).*
  - *Transport the TA from the contractor facility to Sandia Albuquerque.*
  - *Perform commissioning tests on the TA to verify functionality.*
  - *Open the Nuclear Technology Users Facility (NTUF) for commercial component demonstration testing.*

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Recent Modeling Accomplishments

Example output from models

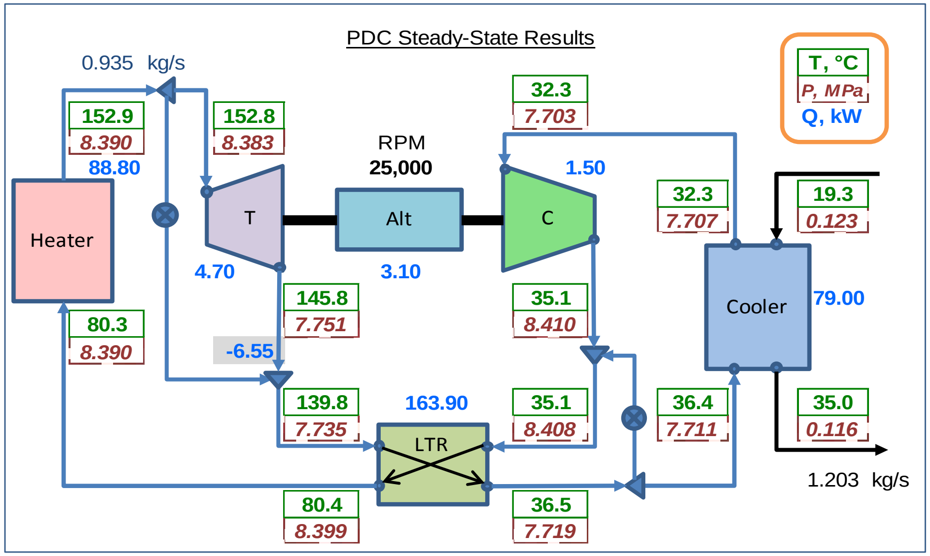


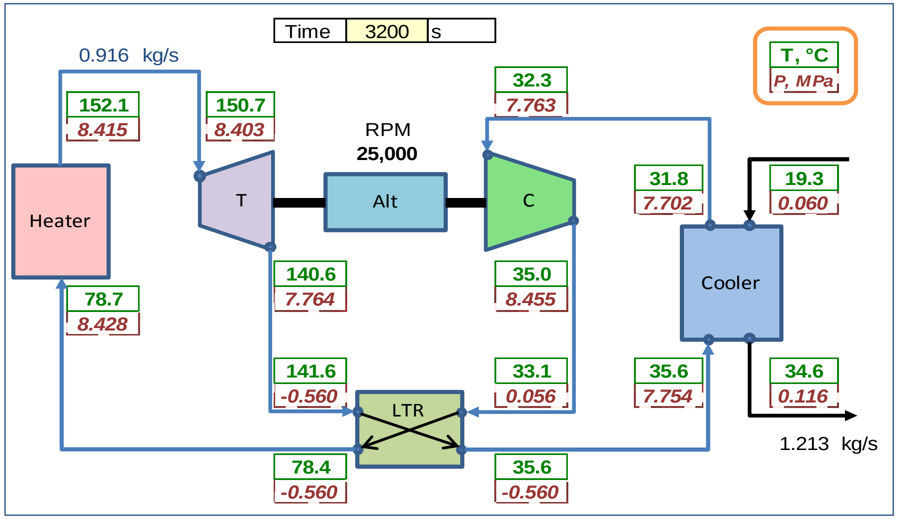
- **Modeling tools developed that can predict Brayton cycle gross efficiency for any combination of the following variables.**

- *Simple or split flow configuration*
- *Heat rejection temperature (low temperature)*
- *Turbine inlet temperature (high temperature)*
- *Compressor inlet pressure (low pressure)*
- *Compressor discharge pressure (high pressure)*
- *Recuperator efficiencies*
- *Turbine and compressor efficiencies*
- *Component pressure drop*
- *Working fluid*

Steady-State Results

- **The results of the steady-state calculations from the Plant Dynamics Code (PDC) model are surprisingly close to the experimental data**
  - Pressures, temperatures, flow rates
  - Despite all the uncertainties of the experimental data
  - Special adjustments for heat loss were needed





Experimental Data

Code Prediction

Analysis of SCO_2-Lubricated Bearings

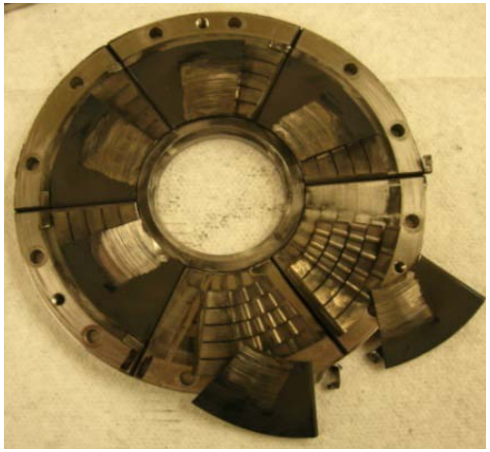
- **Background**
  - **SNL has developed flow loops for demonstrating the feasibility of the S-CO_2 Brayton cycle.**
  - **The loops are driven by turbomachinery running on gas foil journal and thrust bearings.**
    - *Gas bearings provide oil-free radial and axial support at high temperatures and speeds, and are an 'enabling technology' for microturbine systems such as the SNL facilities*
    - *But they are an emerging technology with few manufacturers and little performance data available*

- **Problem and Proposed Solution:**
  - **Models for power loss and thrust load capacity for compliant foil bearings do not exist, yet these are of great importance in understanding operating limits of the Brayton cycle hardware.**
  - **Thrust bearings analysis codes validated by experimental data are needed to understand the impact of operational parameters on bearings performance**

This work will allow the DOE S-CO_2 Brayton loop to generate more electricity, at higher efficiency.

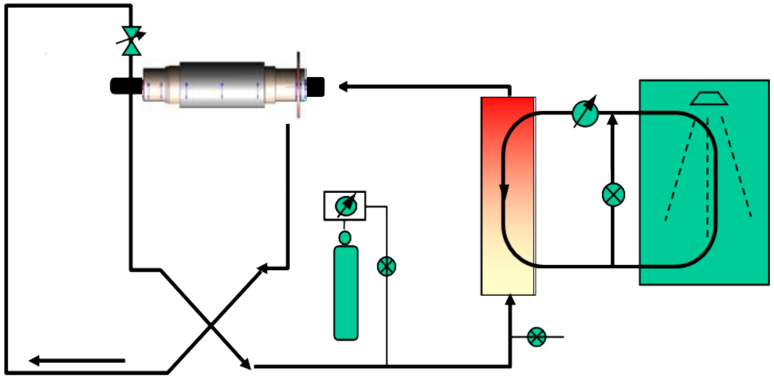
– **Currently the loop is limited by thrust bearing performance: 60,000 rpm has been reached, short of the 75,000 rpm design point**

– **Mechanisms to decrease frictional heating while maintaining load capacity will soon be needed.**



Experimental Thrust Bearings Test Rig

- **A thrust bearings test rig has been built in Bldg 6630 at SNL**
  - Advanced bearings designs are currently being evaluated for potential to reduce friction
  - Load capacity, friction are being measured for different operating conditions
  - Data will benchmark the code, allowing the model to be used for design of upgraded bearings in the near future.
  - Also, successful performance of the new bearings on the test rig will prove they are able to support thrust loads on the DOE SCO_2 Brayton cycle test loop



Pictured: *Failure of an advanced thrust bearing design*

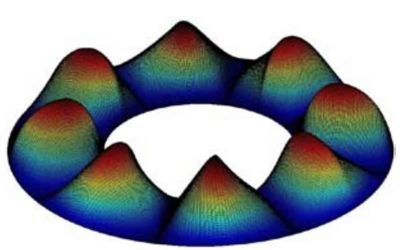
- **FY12 Goals:**
- Characterize thrust loads during typical SCO_2 Brayton loop startup/shutdown transients to confirm that the new bearings can support maximum expected loads.
- Conduct further experimental tests for a range of speeds 25000-75000 rpm, bearings pressures from 200-800psi, loads of 100-400lbs

Thrust Bearings Modeling

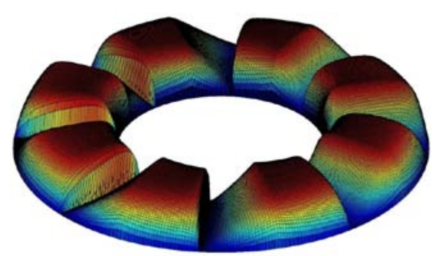
- **A new code has been developed for analysis of compliant thrust bearings**
  - Isothermal elastohydrodynamic model has created by evaluating the turbulent Reynolds Eqn.
  - Code solves for fluid velocity field, load capacity and frictional power loss, is linked to NIST - RefProp for dynamic updating of CO_2 fluid properties

$$\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r} G_r \bar{\rho} \bar{h}^3 \frac{1}{\bar{\mu}}\frac{\partial \bar{p}}{\partial \bar{r}}\right)+\frac{1}{\bar{r}^2}\frac{\partial}{\partial \theta}\left(G_\theta \bar{\rho} \bar{h}^3 \frac{1}{\bar{\mu}}\frac{\partial \bar{p}}{\partial \theta}\right)=\Lambda\frac{\partial\left(\bar{\rho}\bar{h}\right)}{\partial \theta}$$

- **The code has been successful in explaining unexpected phenomena observed during experiments**
  - Modeling has shown that the lubrication layer is in the highly turbulent regime, accounting for the very sensitive relationship between friction and lubricant density observed
  - The high-rpm saturation of load capacity has been explained by the profile of the building lubrication pressure at the thrust pads.



Low rpm



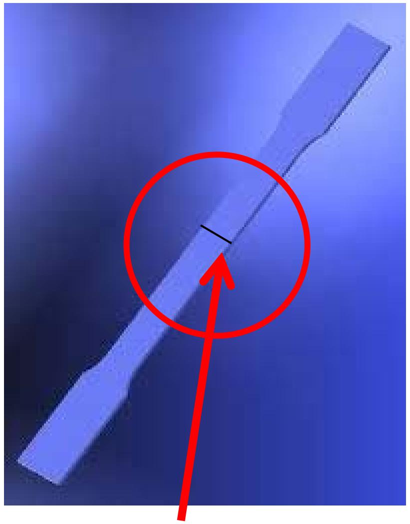
High rpm

Pictured: *Pressure profiles of a thrust bearing evaluated using the new code*

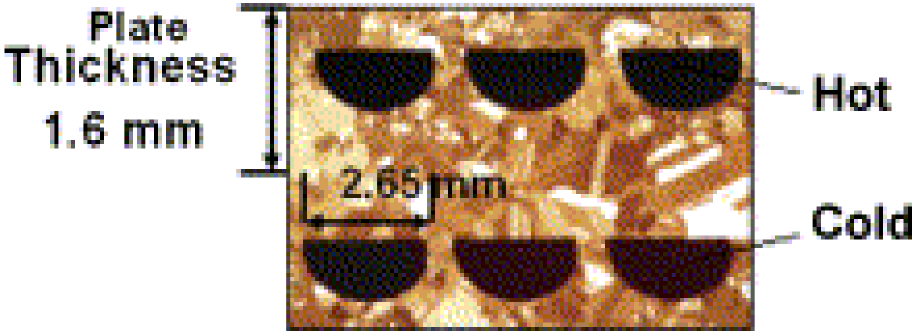
- **FY12 Goals:**
  - Add temperature dependence to the fluid/structure models, work on comparison of the simulated results to experimental data.

Heat Exchanger program

- **Prepare a Federal Business Opportunity (In process)**
- **Select contractor**
  - Fabricate ASTM stress coupons to validate diffusion bonding as a structural support mechanism. Validation will take place on an Instron machine output results σ vs. ε
  - Fabricate NQA1 printed circuit heat exchangers. Idea is to fabricate one large diffusion bonded heat exchanger (4'x4'), separate into 16 separate heat exchangers and make necessary manifold connections so they can perform as 16 heat exchanges separately.
  - At site host hydro test to failure each heat exchanger to investigate failure mechanisms of the heat exchangers. Also investigate the sodium to SCO2 interface within the heat exchanger.



ASTM sample to test strength of Diffusion Bonding



Metal Corrosion in Supercritical CO_2 and Liquid Sodium

- **A review report titled: Metal Corrosion in a Supercritical Carbon Dioxide – Liquid Sodium Power Cycle has been completed and submitted.**
- **The report consisted of a gap analysis that identified the following areas for additional work:**
  - Corrosion testing in supercritical CO_2 needs to be performed with metal coupons under stress. Experience gained with the operation of the Magnox CO_2 cooled reactors indicates the most severe corrosion was observed for components under stress.
  - The effects of water, oxygen and other impurities need to be examined in more detail. The literature indicates water at ppm concentrations creates a very corrosive environment for many metals in the presence of CO_2.
  - Tests need to be performed for diffusion bonded materials in liquid sodium. No information is available in the literature on this topic.
  - Additional testing at high temperatures, 300 – 600°C, needs to be performed to understand the mechanism of carburization in liquid sodium as this will likely be one of the most significant mechanism for corrosion in this system.
  - A small microchannel heat exchanger constructed by diffusion bonding needs to be tested under operational conditions with supercritical CO_2 and liquid sodium.
  - Most or all of the work can be performed at the existing facilities at Argonne National Laboratory.

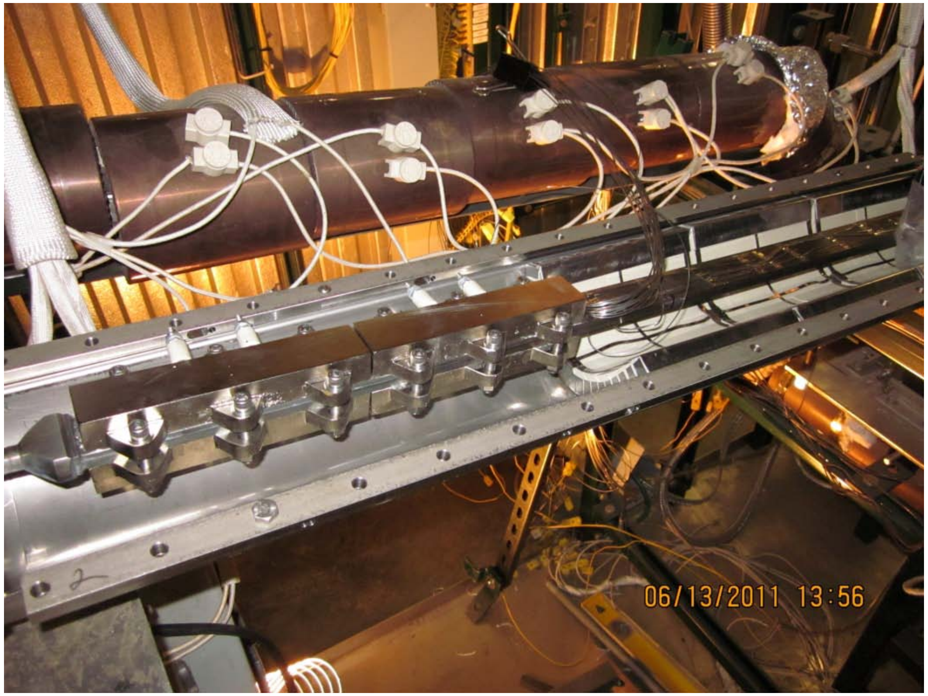
Flowing Sodium Cooled by Air Flowing Over Test Section Causing Precipitation of Sodium Oxide on Wall

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

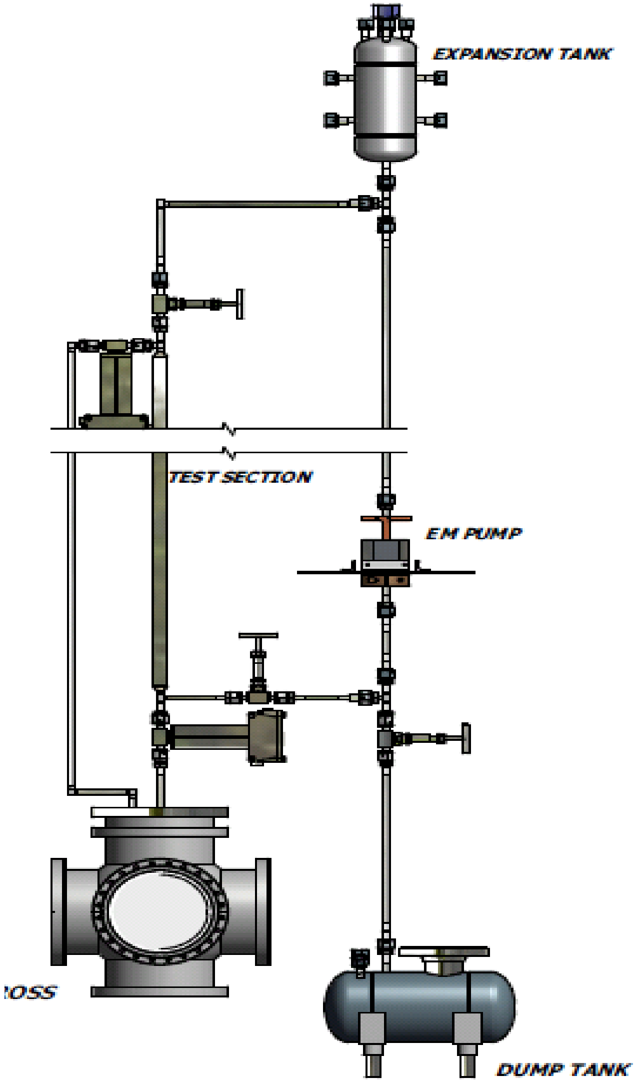
1,800 cubic feet per minute (cfm) air blower with variable frequency drive for controlling air velocity and chiller

Test section and heaters inside of stainless steel air duct half-wall



Small-Scale Sodium Drain and Fill Tests

- **In case of sodium leak, intermediate sodium circuit normally drained of sodium to limit spillage and sodium fire**
  - Seek drain time of about 15 minutes
  - Small sodium channels of compact heat exchangers must be demonstrated to drain efficiently
- **Test section is contained on a tilting assembly such that the orientation can be varied from vertical to horizontal**
- **Test section drains into a six-way cross**
- **Test section drained under Argon**
- **Test section is instrumented – Ultrasonic detection of time dependent draining film thickness to be investigated**
- **Various test sections with different channel geometries**
- **Sodium loop for wetting of stainless steel by sodium prior to tests**

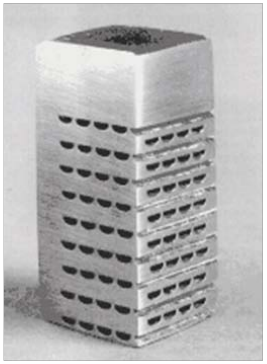


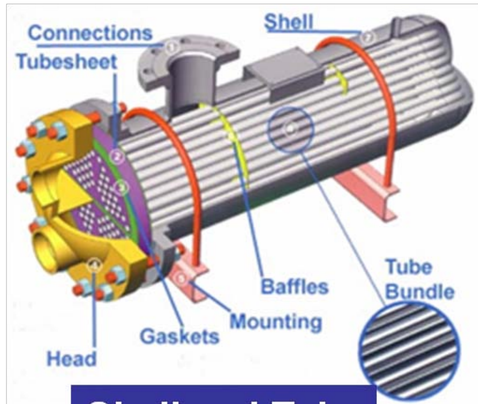
Fundamental Sodium-CO_2 Interaction Tests

- **Small-scale sodium facility is being assembled to provide fundamental data on interactions between sodium and CO_2 released into sodium through stainless steel micro-leak configurations and self-plugging of stainless steel micro-leak configurations under realistic conditions of sodium-to-CO_2 heat exchanger failure**
- **Envisioned failure mode for compact diffusion-bonded heat exchangers involves formation of microcracks limiting flow of CO_2 into sodium with possibility of self-plugging of crack channels due to formation of solid reaction products**

Technology Development

Compact (PCHE)





Shell and Tube

Basic material properties →

Fabrication Methods:
- Diffusion welding
- High Temperature Brazing
- Dissimilar metal welds
- Metal-ceramic joining
- ASME properties/design rules

Mechanical SETs:
- Full T and P
- ASME proof testing
- Joined test specimens
- Pressure transients

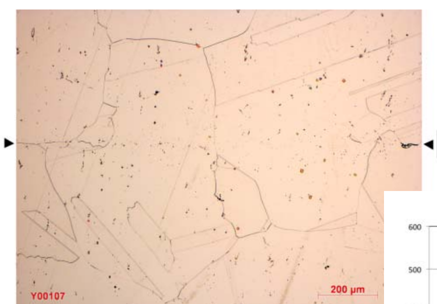
Corrosion Testing:
- KF-ZrF_4 &/or other salts
- Supercritical steam
- Alloy &/or other alloys
- Joined specimens
- Mechanically loaded

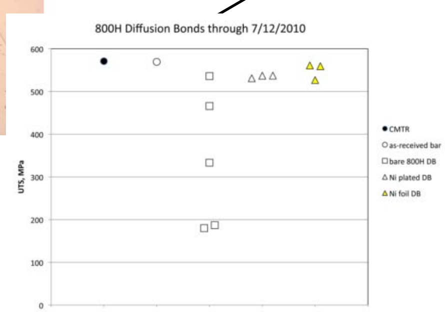
Thermohydraulic Performance SETs:
- Full or scaled T and P
- Scaled flow
- Salt coolant
- Post test analysis for environmental effects

Integrated Testing:
- KF-ZrF_4 &/or other salts
- Supercritical steam
- Full T & P
- Chemistry control
- Scaled flow

Component Demonstration Successful

Component predicted to deploy successfully



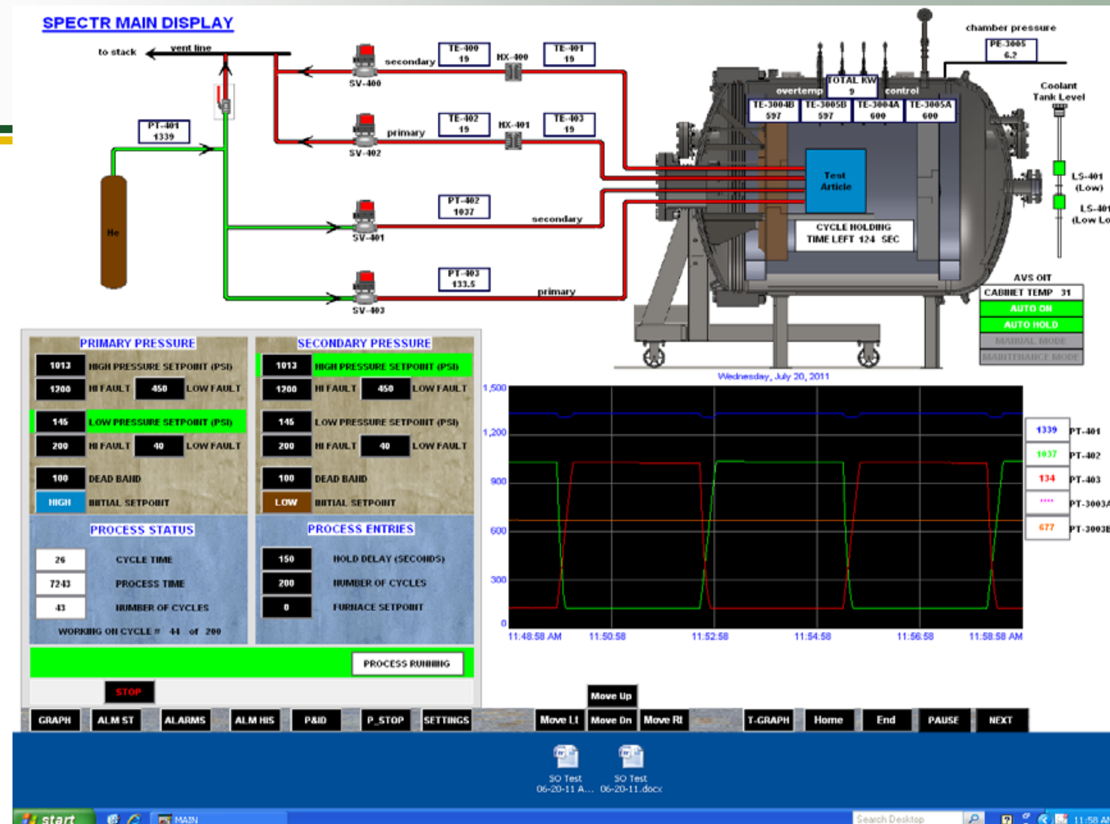


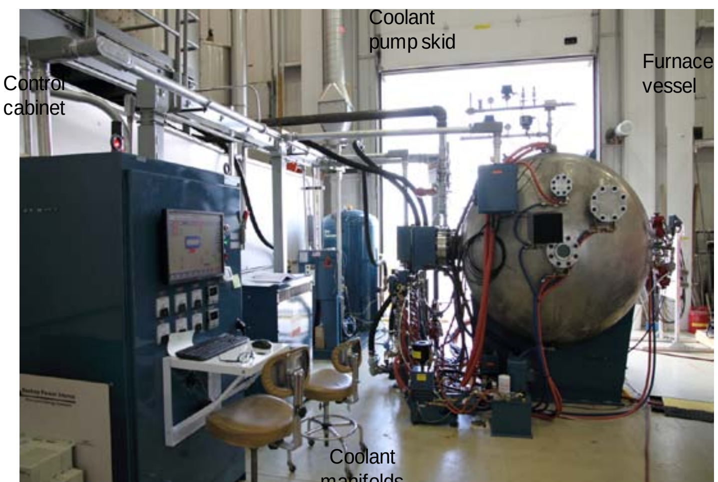
TRL 3 | TRL 4 | TRL 5

Increasing technical maturity →

SPECTR: *Single effects testing of cyclic pressure transients at operating temperature*

- *Demonstrates TRL 4 for SHX*
- *Needed for ASME Section 3, HH qualification of diffusion welds*
- *Potential savings of over $250M*





Expected FY 2012 Accomplishments

- Install and commission the DOE-NE closed Brayton cycle TA at Sandia, Bldg 6630. Completing the 1st phase of the Sandia Nuclear Energy Systems Laboratory/Nuclear Technology User Facility/Brayton Systems Labs. (Low Pressure Closed Brayton Cycle, Supercritical Fluid Brayton Compressor Laboratory, and Split Flow-Fully Recuperated Supercritical CO2 Brayton Cycle). Release produced power to local grid.
- Adapt Brayton Laboratory to the customer cycle and generate results and report that justify continued funding for FY 13 from the industry customers.
- Begin In-depth Corrosion Studies and Domestic Compact Heat Exchanger Development
- IF DOE-EERE SunShot proposal is funded, perform initial sizing and configuration studies. Evaluate Sandia NTUF/Phase 2 as a 10 MWe TA site host. Power to be delivered to local grid
- Initiate EPRI power study
- Complete conceptual design of SEP and initiate Phase 2.

ANL Energy Conversion Technology Team

- Jim Sienicki
- Anton Moisseytsev
- Rick Vilim
- Yoichi Momozaki
- Dave Chojnowski
- Dae Cho
- Claude Reed
- Craig Gerardi
- Dennis Kilsdonk
- Mitch Farmer

Molten Salt Reactor Heat Exchanger

- **Michael G. McKellar**
- **Piyush Sabharwall**
- **Denis Clark**

Supercritical Carbon Dioxide Brayton Cycle Development at Sandia National Laboratories

Sandia Brayton Cycle Team

ARC Team

Jim Pasch – PI
Tom Conboy – Lead TAC Engineer
Darryn Fleming-Lead Mechanical Engineer
Robert Moore – Lead Chemical Engineer
Robin Sharpe – Lead Technologist
Bob Fuller – BNI, PI

SMR Team

?– PI
?– Lead TAC Engineer
? - Lead Mechanical Engineer
? – Lead Chemical Engineer
? – Lead Technologist
? – BNI, PI

SEP Team

Bobby Middleton – PI
William Martin – Brayton Systems Engineer
David Ames – Lead Systems Engineer
Julius Yellowhair – Solar Receiver Engineer

Industrial Development Team

Gary Rochau – PI
Angie Dyke/Sarah Hannigan – Financial Analysis
Bianca Thayer – Licensing Executive
Brooke Marshall – Technology Transfer Executive
Laura Dalton – Non Disclosure Agreements
Lynette Rocheleau – Copyrights
Dan Jenkins - Patents

Commercialization Approach

- **Secure Intellectual Property**
  - Export Control Determination
  - US Competitiveness Determination
  - Patents
  - Patent Disclosures
  - Copyrights
- **Announcement of Intent to Collaborate**
  - Federal Business Opportunities
  - Non-Disclosure Agreements
  - S-CO2 Symposium
- **Development of Collaboration Tools**
  - Cooperative Research and Development (Funds-In)
  - Work For Others Agreements (Private Contracts)
  - Joint Proposals (responding to Broad Area Announcements)
- **Establish Nuclear Technology User Facility**
  - Gain square footage for user defined experiments – Leveraging legacy remediation
  - Establish capabilities supporting experiments (S-CO2 loops, models, technical support)
  - Financial Processes to support user defined experiments (Using solar test facility models)

Technology Development Efforts

- **DOE-EERE Sunshot FOA proposal**
  - NREL, EPRI, and industry participants
  - 10 MWe SCO2 Brayton technology – NG Heated
  - Concentrated solar power applications with dry cooling.
  - Power Returned to local Grid
- **DOE-NE Brayton cycle Test Assembly(TA) testing capabilities at Nuclear Technology User Facility(NTUF)**
  - Reconfiguration of Sandia Brayton Loops
  - Likely established NTUF's first commercial customer
  - First test results required by October 1, 2012.
  - Specific objectives for near-, mid-, and long-term testing of the TA are being developed.
- **Risks to the smooth and continued access to TA testing are being identified, and contingency plans developed to minimize down time.**

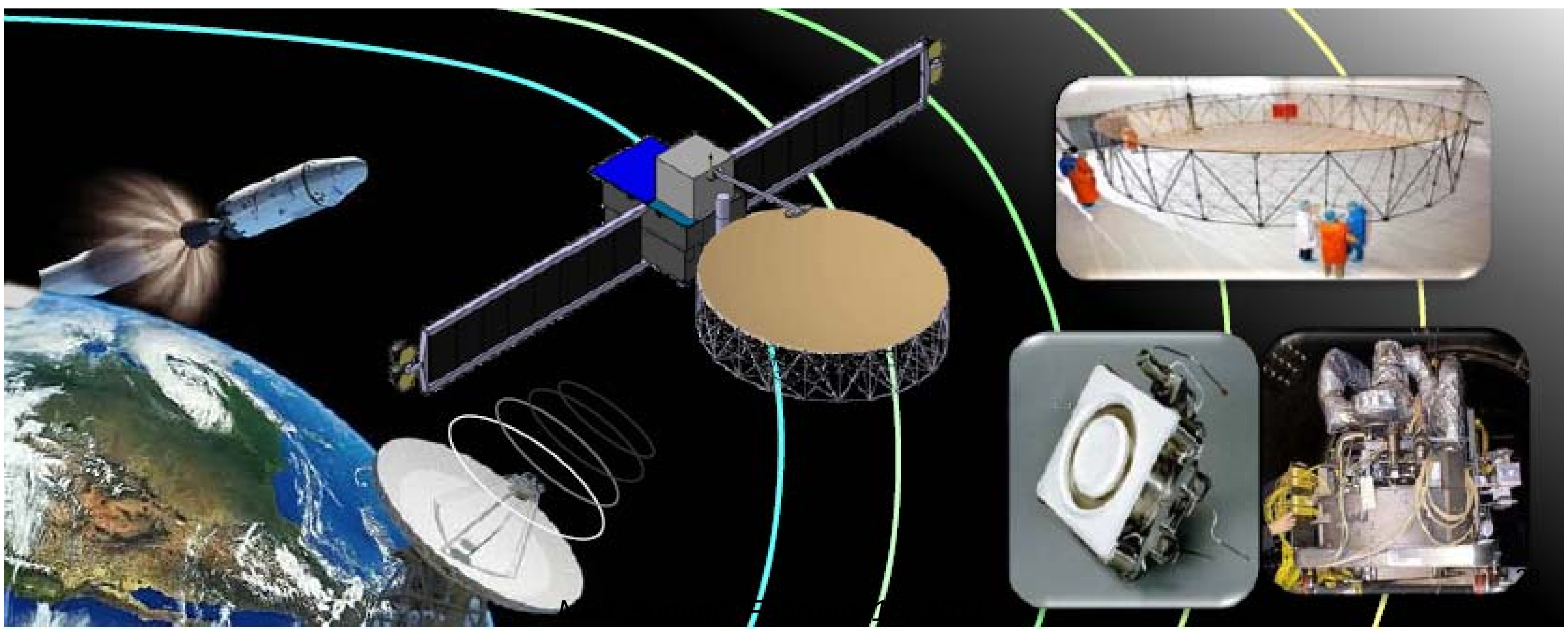
Technology Development Efforts (Continued)

- **GE-Global funding project for development of a 10 MWe bottoming cycle for Gas Turbines**
  - User facility application in initial phase
  - Configuration is DReSCO
- **Collaborating with EPRI on mutually beneficial studies regarding the application of SCO2 closed Brayton power conversion concepts to traditional EPRI customers**
  - Coal-fired (including current and future Ultrasupercritical Steam Plant designs)
  - Concentrated Solar Thermal
  - Geothermal
  - Nuclear
  - Topping and bottoming cycles.
- **Collaboration with EPRI includes**
  - Exhaustive literature search
  - Theoretical cycle performance modeling
  - Establishment of realistic performance specifications of the major cycle hardware components

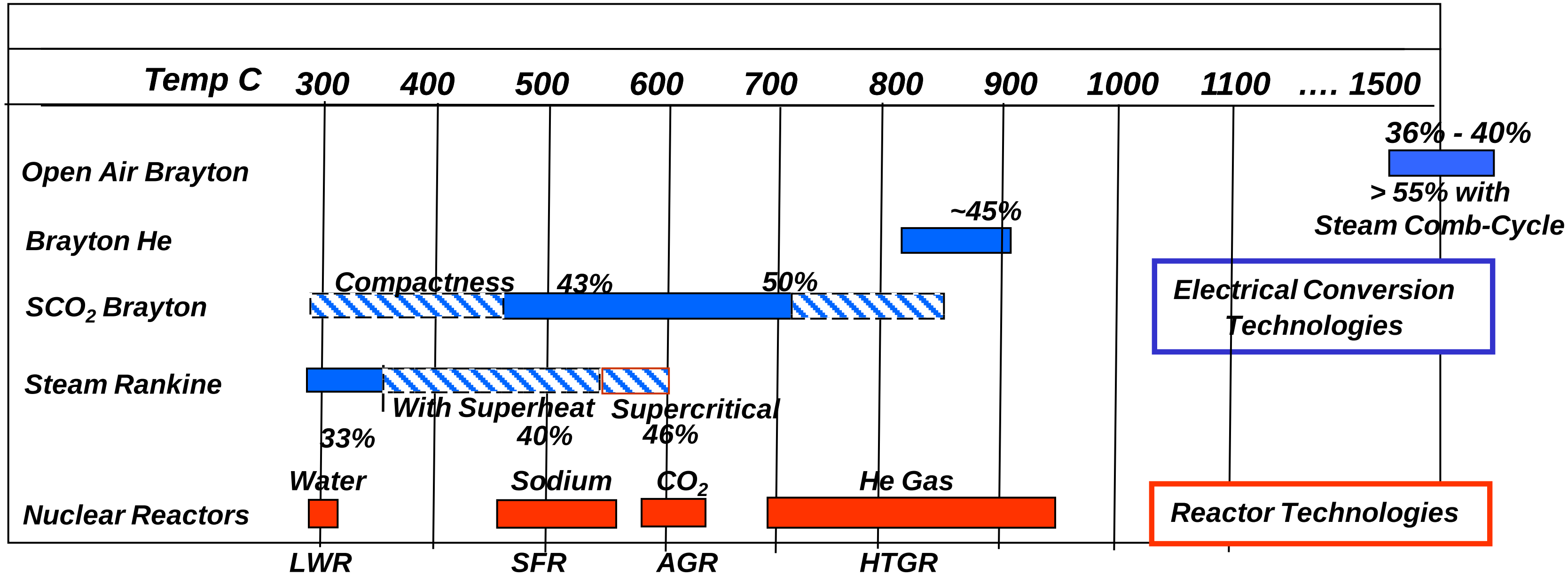
Technology Development Efforts (Continued)

- **Cooperative Research and Development Agreement signed with Northrup Grumman-Aerospace**
- **Development of a Solar-Electric-Propulsion (SEP) for space tug applications to move satellites from low earth orbit to high earth orbit.**

- *Phase 1 is development of a conceptual design at TRL level 3*
    - *Low Pressure Brayton Loop is prototype (He-Xe)*
    - *Concentrated Solar heat exchanger is the critical component*
    - *3 month time line*
- *Phase 2 is construction of prototype hardware for earth base demonstration to take technology to TRL level 7-8*
    - *2 year time line*
- *Phase 3 is launch of a 150 KWe demonstration*
- *Phase 4 is launch of a 300 KWe demonstration*



Power Conversion and Nuclear Reactor Outlet Temperature Ranges



S-CO_2 Power Conversion Operating Temperatures Matches all Advanced Reactor Concepts
LWR – compactness, condensing cycle appear promising

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

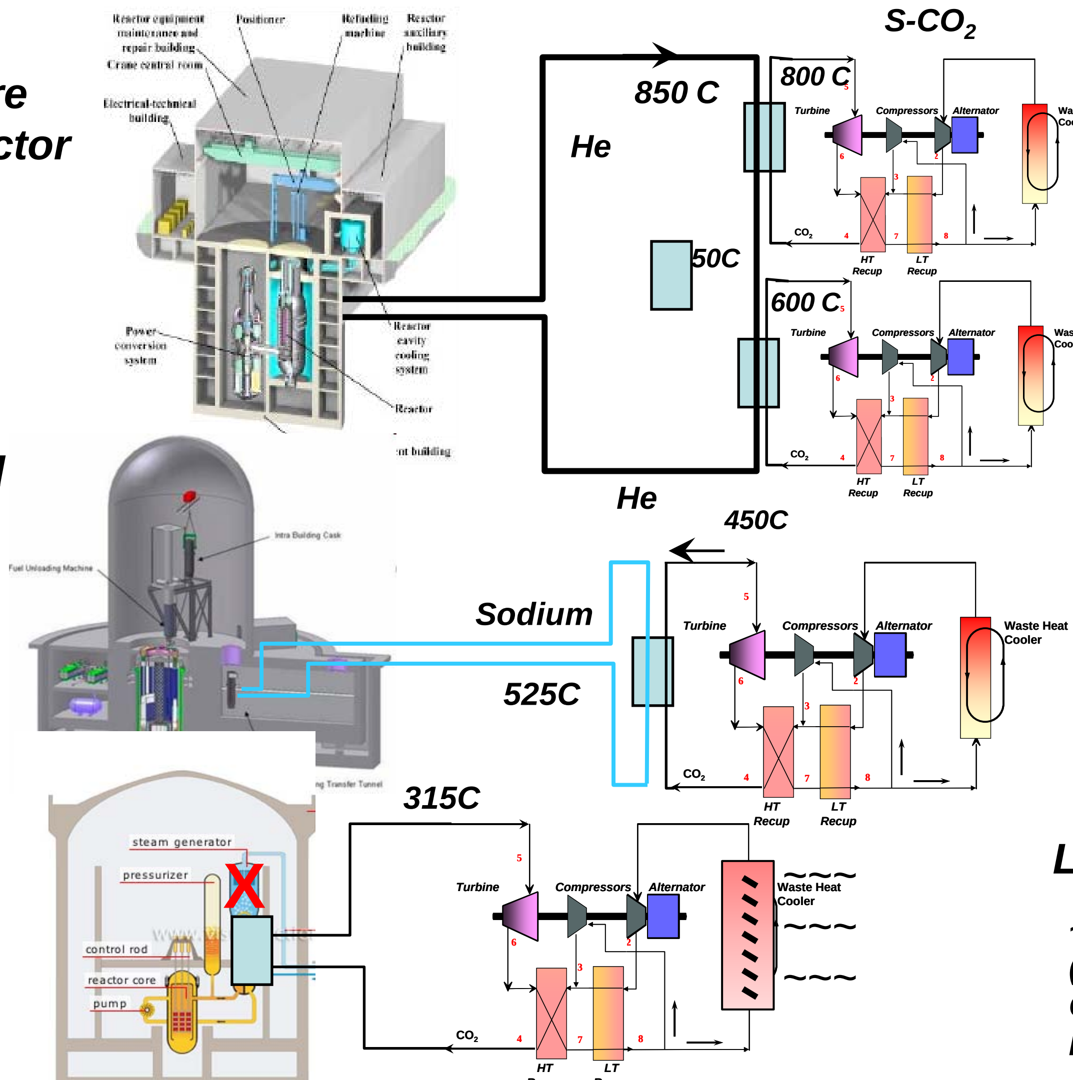
S-CO_2 Power Cycles for Reactors

NGNP
High Temperature Gas Cooled Reactor
850-900 C

Sodium Cooled Reactor
500-550 C

LWRs
Pressurized Water Reactor
330 C

Potential SMR Applications



~ 54 %

~ 46 %

GCRs

~ 50 % Efficiency (S-CO_2 Brayton)

SFRs

~ 44 % Efficiency (S-CO_2 Brayton)

LWRs

~ 40 % Efficiency (S-CO_2 Recup Rankine Condensing Brayton with Dry Heat Rejection)